Discussion of needed technologies for fusion power plants

Council on Ionizing Radiation Measurements & Standards Meeting (CIRMS Meeting)
Sam Wurzel
Technology to Market Advisor
U.S. Department of Energy, ARPA-E

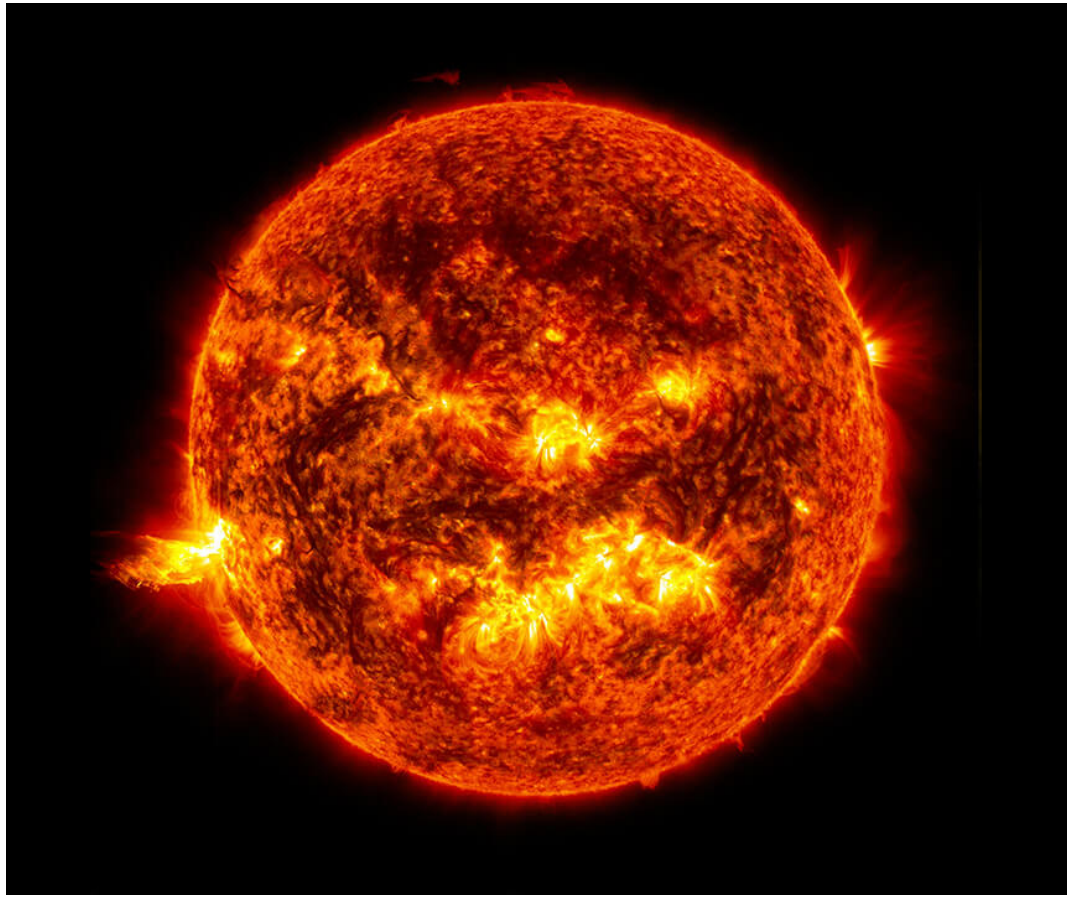
April 19th, 2023

Outline

- Brief history and requirements for “useful” fusion energy
- Historical and recent physics results
- Materials challenges
- Fuel cycle challenges
- Other challenges
- Advanced fuels and their tradeoffs
- Future: Bold decadal vision

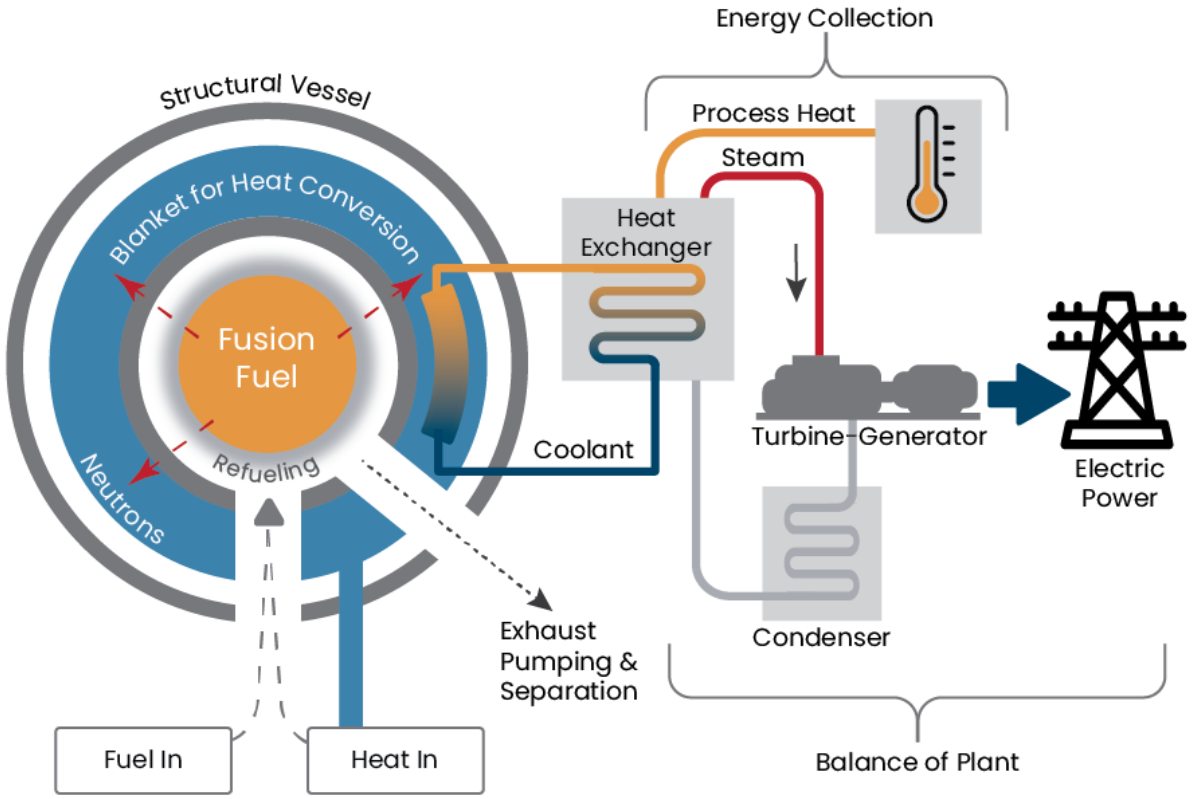
PHYSICS REQUIREMENTS FOR "USEFUL" FUSION ENERGY

Fusion



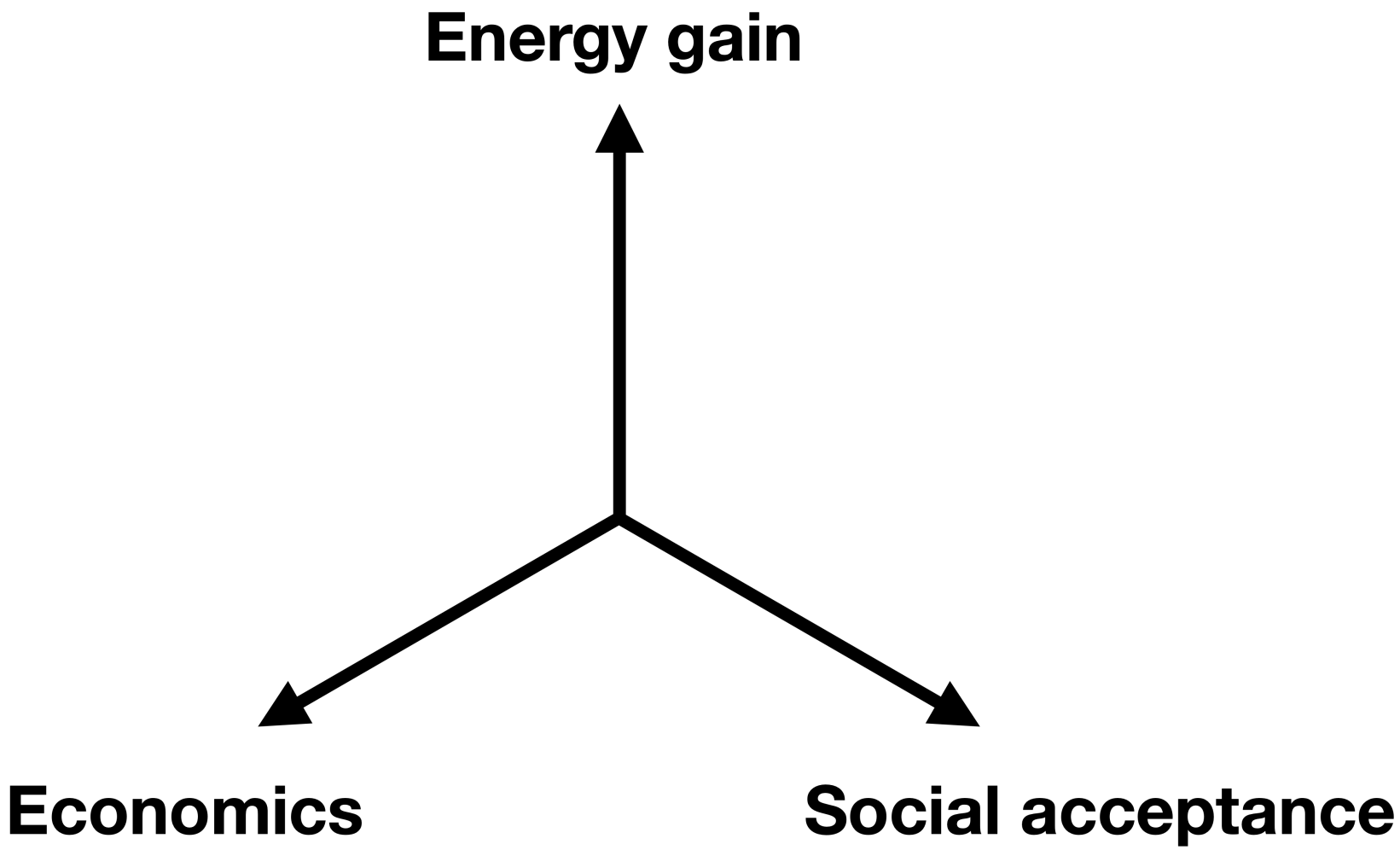
NASA/SDO

Sun



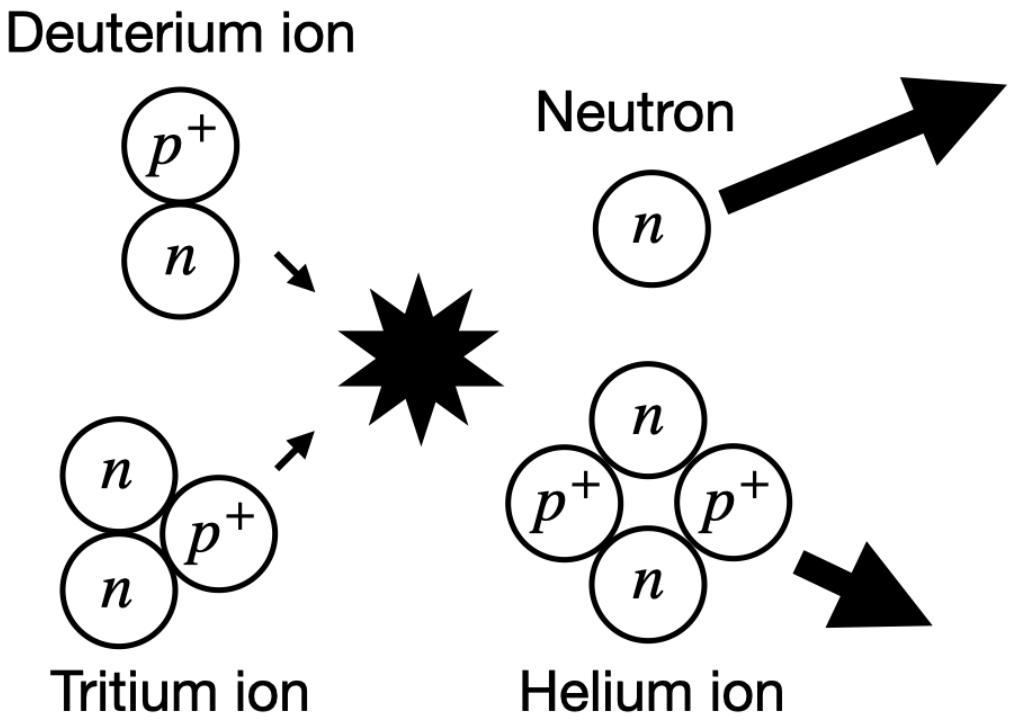
Conceptual fusion power plant

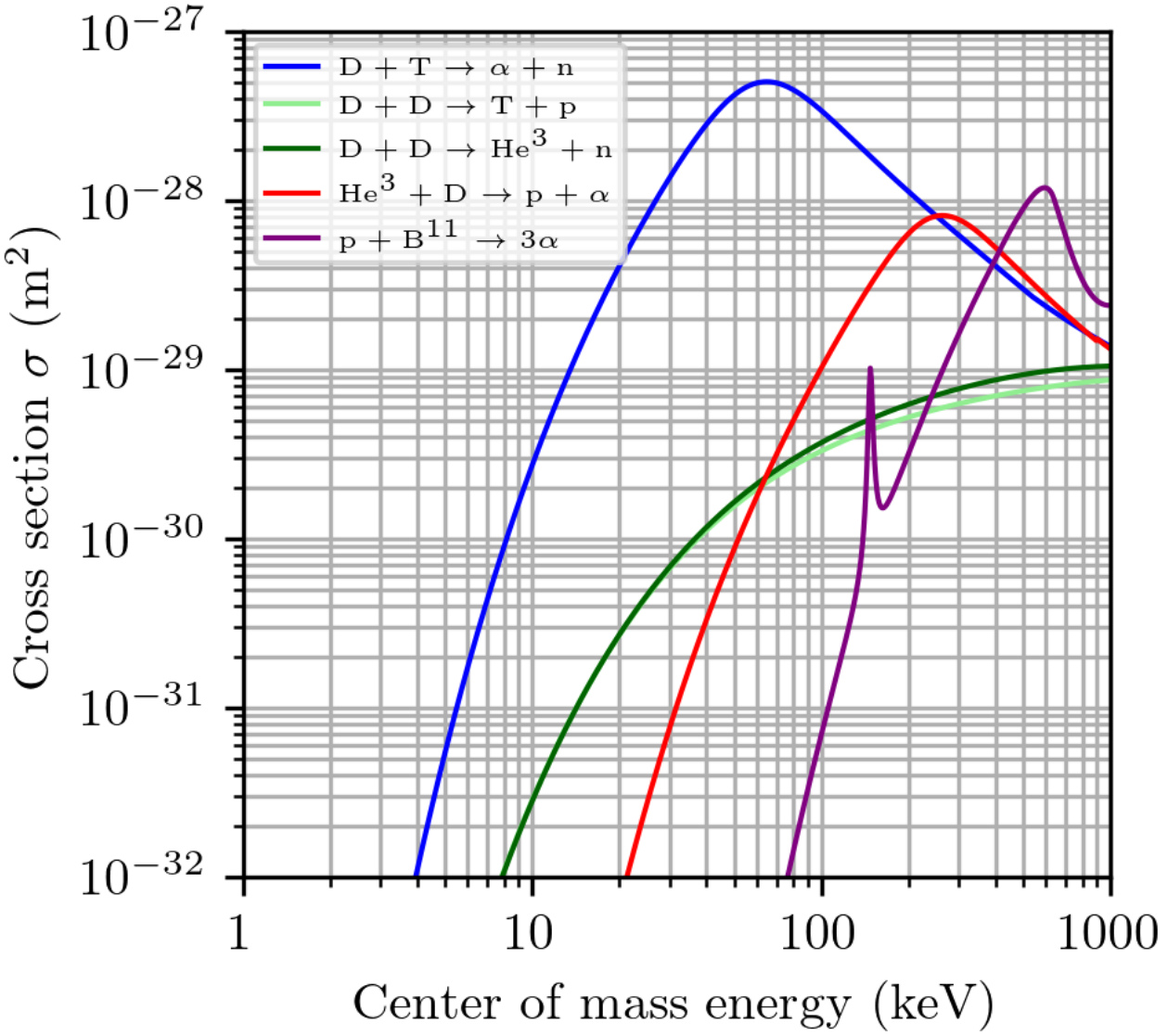
What's needed for commercial fusion energy



Fusion cross sections and deuterium-tritium fusion

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha\,(3.5\,\mathrm{MeV}) + \mathrm{n}\,(14.1\,\mathrm{MeV})$$





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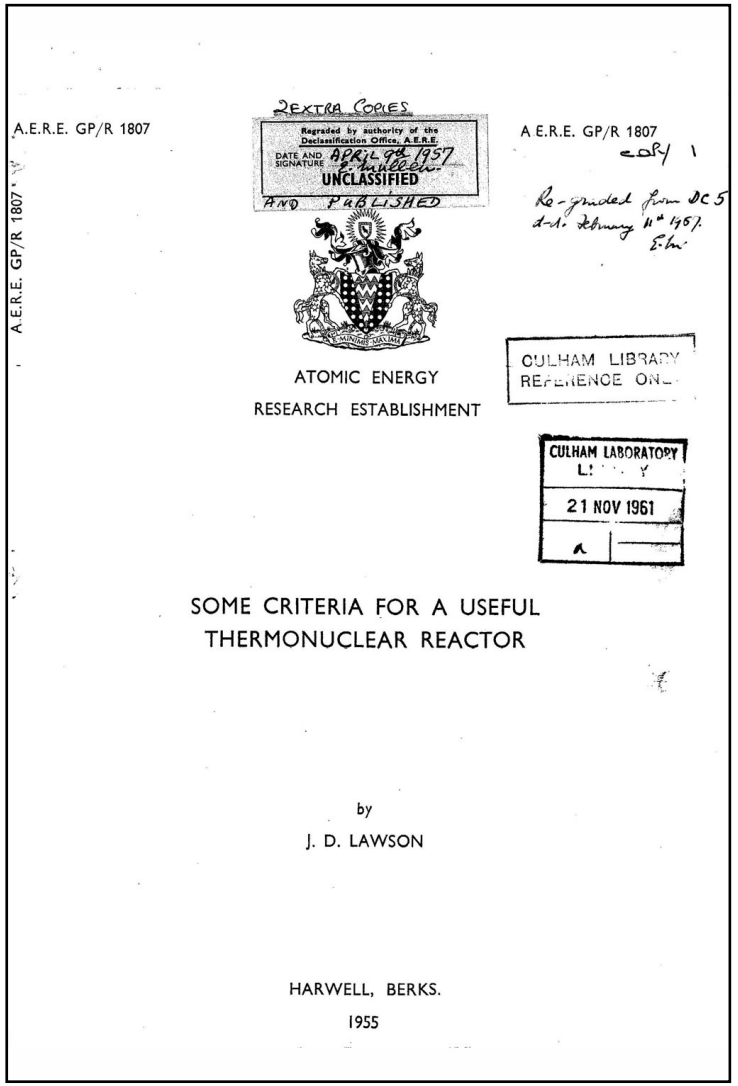
“Some criteria for a useful thermonuclear reactor” Lawson (1955)



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SOME CRITERIA FOR A USEFUL
THERMONUCLEAR REACTOR

by
J. D. LAWSON

HARWELL, BERKS.
1955

INTRODUCTION

In this report the power balance in thermonuclear reactors is considered and criteria which must be satisfied in a useful reactor are found.

...

Various idealized systems will now be analysed. Possible methods of setting up such systems will not however be discussed.

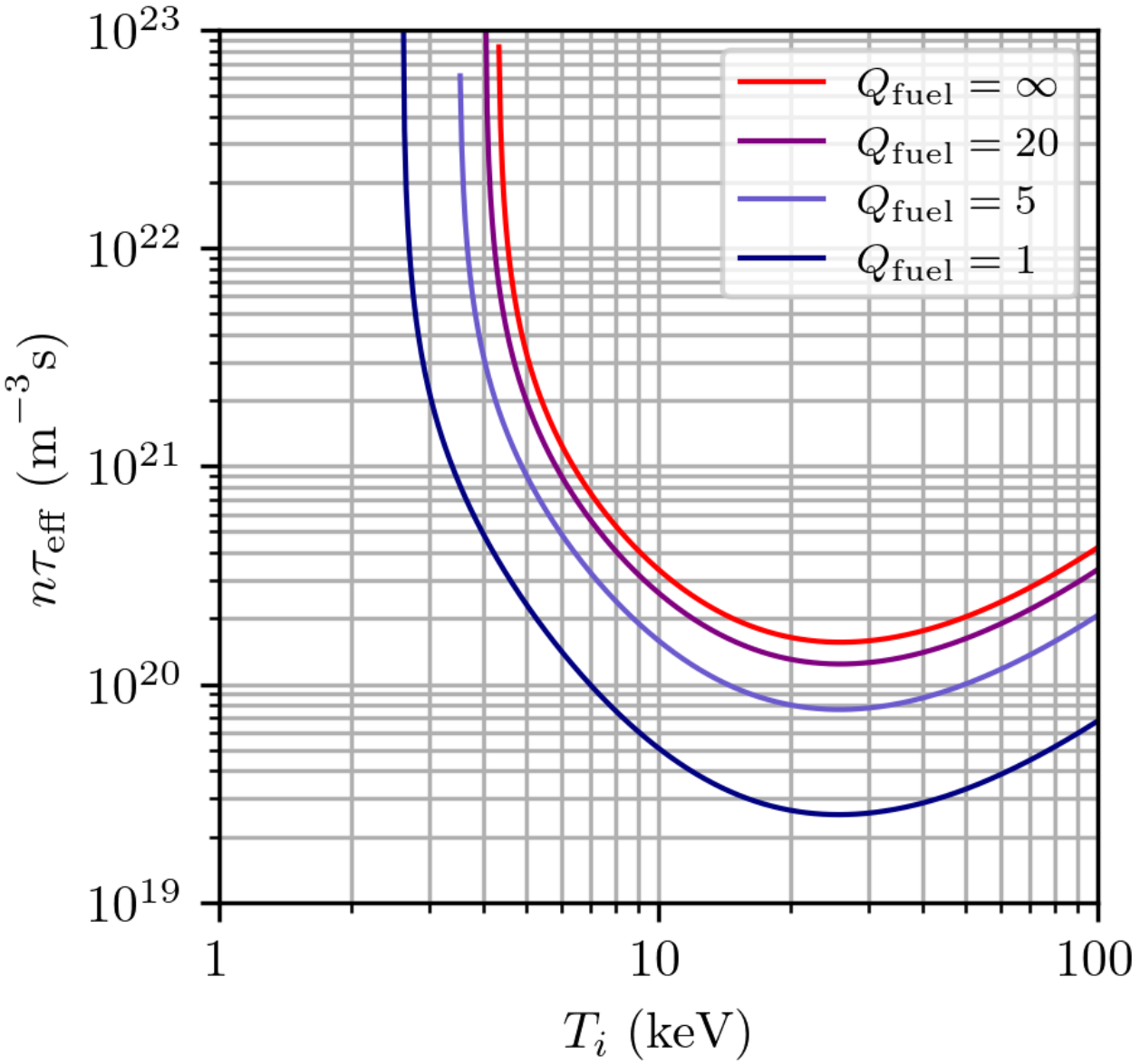
J. D. Lawson, “Some criteria for a useful thermonuclear reactor,” “Technical Report No. GP/R 1807 (1955).

Fuel gain Q_{fuel}

$$Q_{\text{fuel}} = \frac{\text{Fusion energy}}{\text{Heating energy absorbed by fuel}}$$

(Lawson used R)

Large Q_{fuel} requires high threshold of T and $n\tau$



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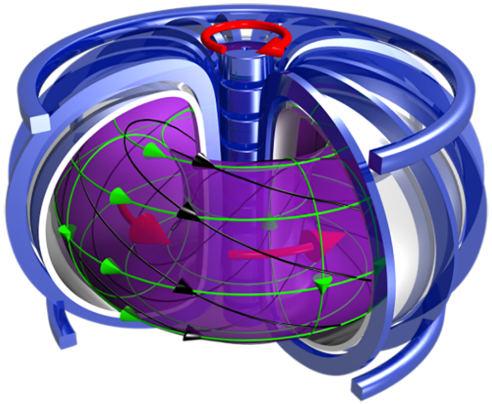
Lawson's conclusion

CONCLUSION

Even with the most optimistic possible assumptions it is evident that the conditions for the operation of a useful thermonuclear reactor are very severe.

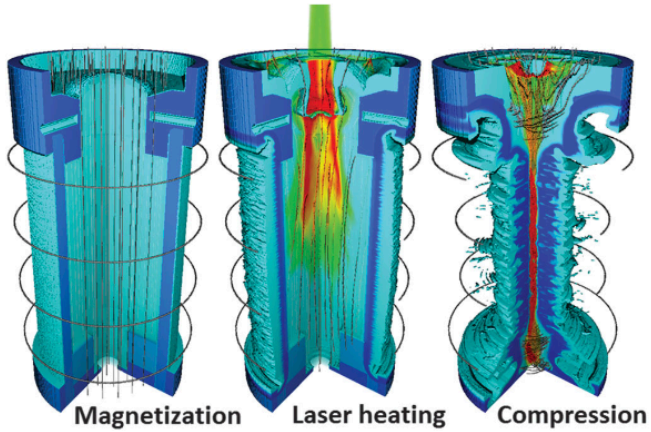
How to achieve high $n\tau$ and high temperature?



Credit: IAEA

Magnetic confinement

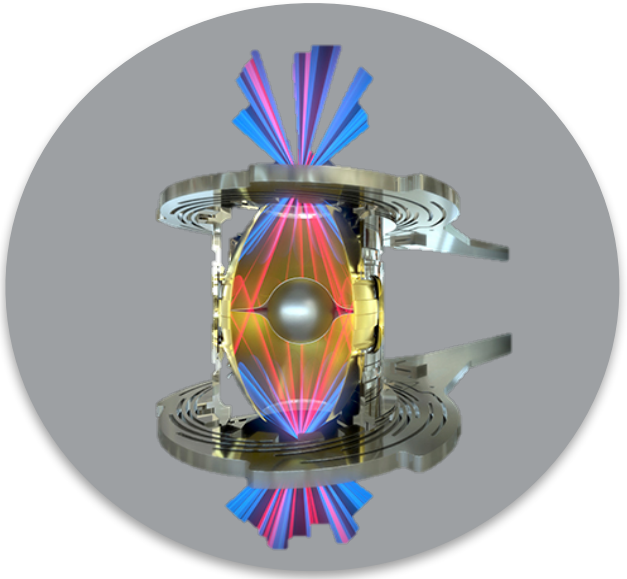
Low n, high τ_E



MagLIF: PRL 113, 155003 Gomez et al. (2014)

Magneto-inertial confinement

Medium n, medium τ_E, τ



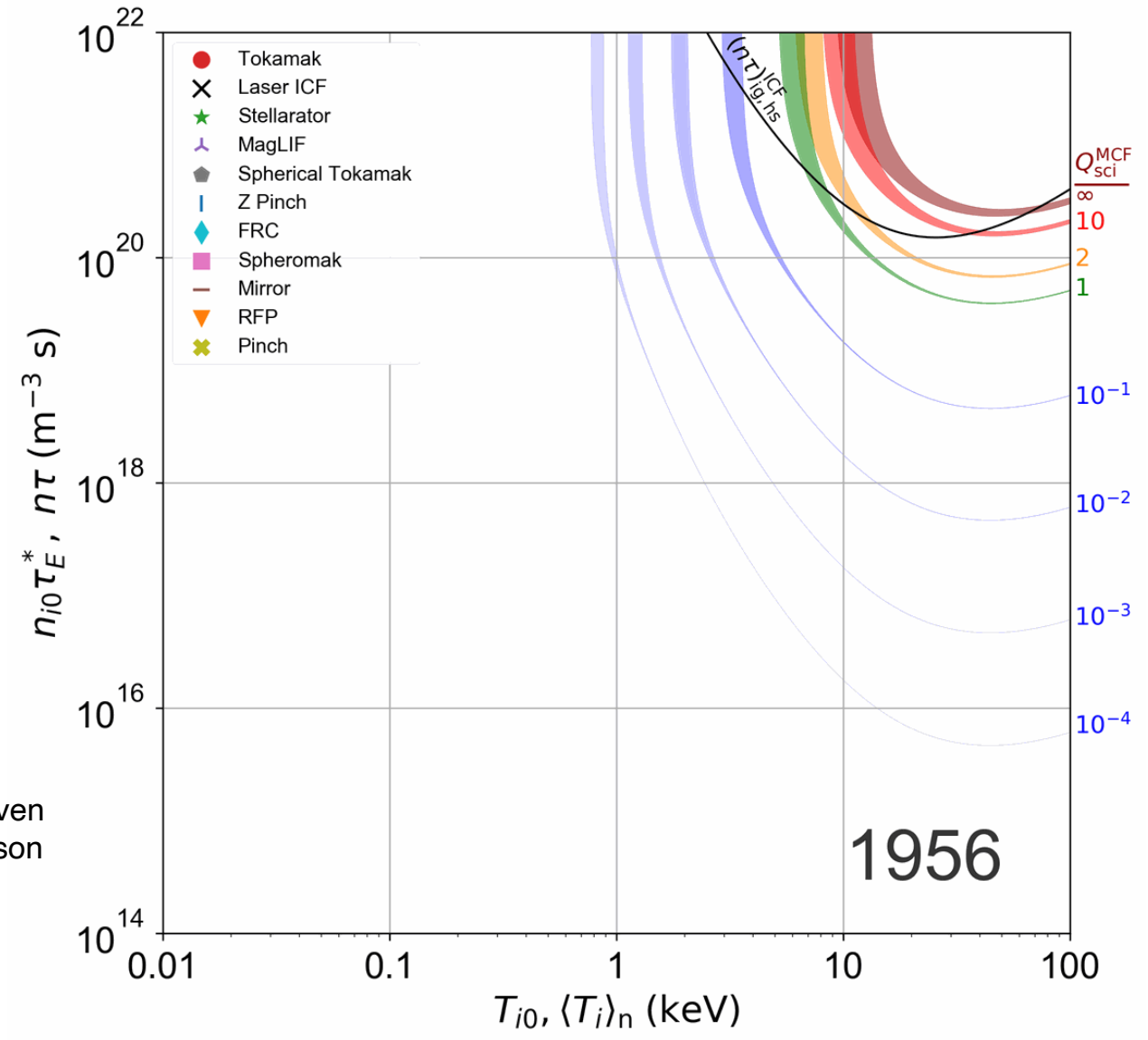
Credit: Jacob Long / LLNL

Inertial confinement

High n, low τ

RECENT RESULTS

Achieved Lawson parameter vs ion temperature



"Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," S.E. Wurzel and S. C Hsu, Physics of Plasmas **29**, 062103 (2022)

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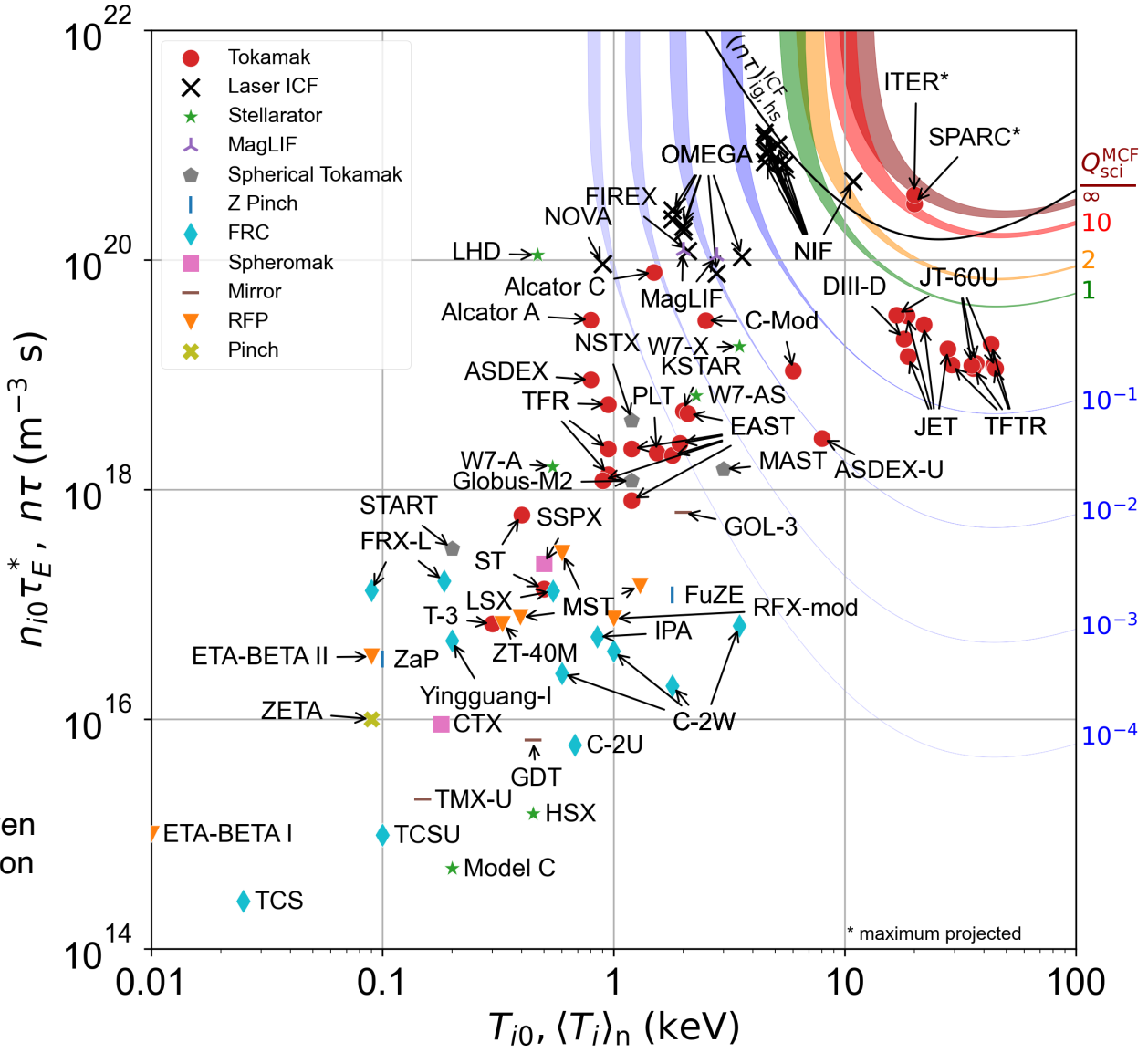
Achieved Lawson parameter vs ion temperature



"Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," S.E. Wurzel and S. C Hsu, Physics of Plasmas **29**, 062103 (2022)

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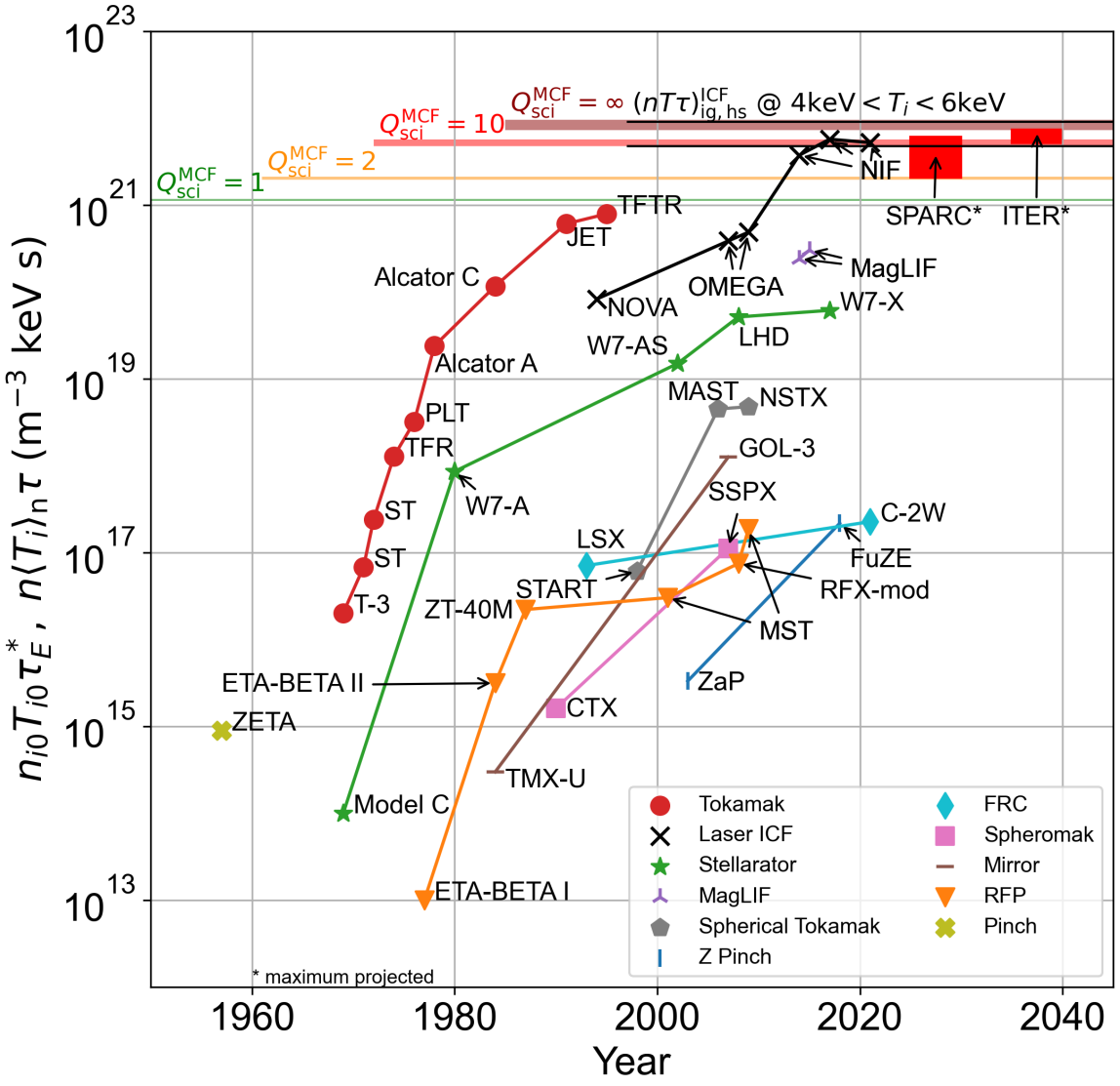
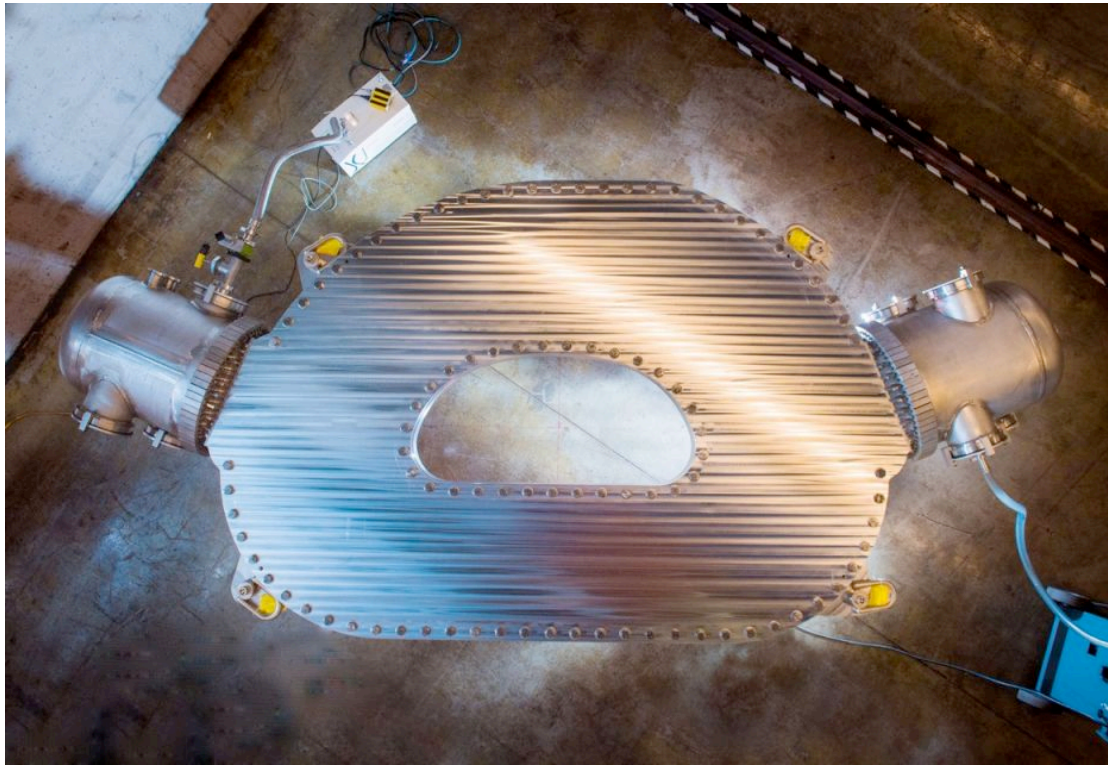
Record triple product achieved over time per concept

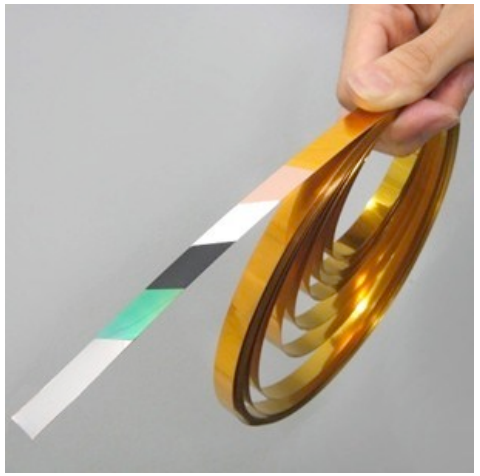


- Caveats:
- Triple product is a coarse figure of merit
- $Q_{\mathrm{sci}}^{\mathrm{MCF}}$ assumes $T \approx 14\ \mathrm{keV}$
- $(nT\tau)_{\mathrm{ig,hs}}^{\mathrm{ICF}}$ assumes $4\ \mathrm{keV} < \mathrm{T} < 6\ \mathrm{keV}$
- Temperature **cannot** be traded off with density or (energy) confinement time

Adapted from "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," S.E. Wurzel and S. C Hsu, Physics of Plasmas **29**, 062103 (2022)

Commonwealth Fusion Systems tests 20T HTS Magnet





September 5th, 2021
Commonwealth Fusion Systems demonstrates 20T toroidal field model coil utilizing high-temperature superconductors

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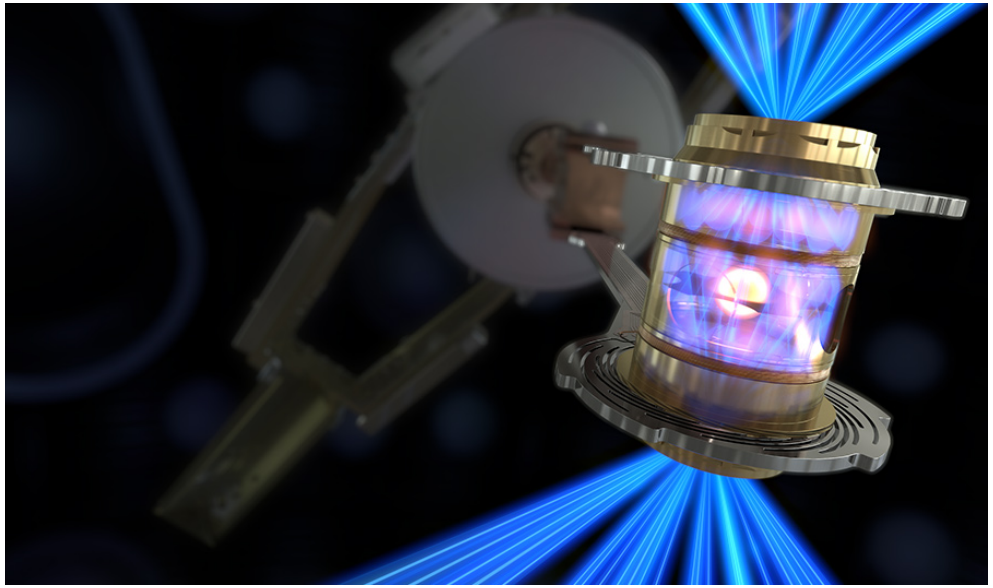
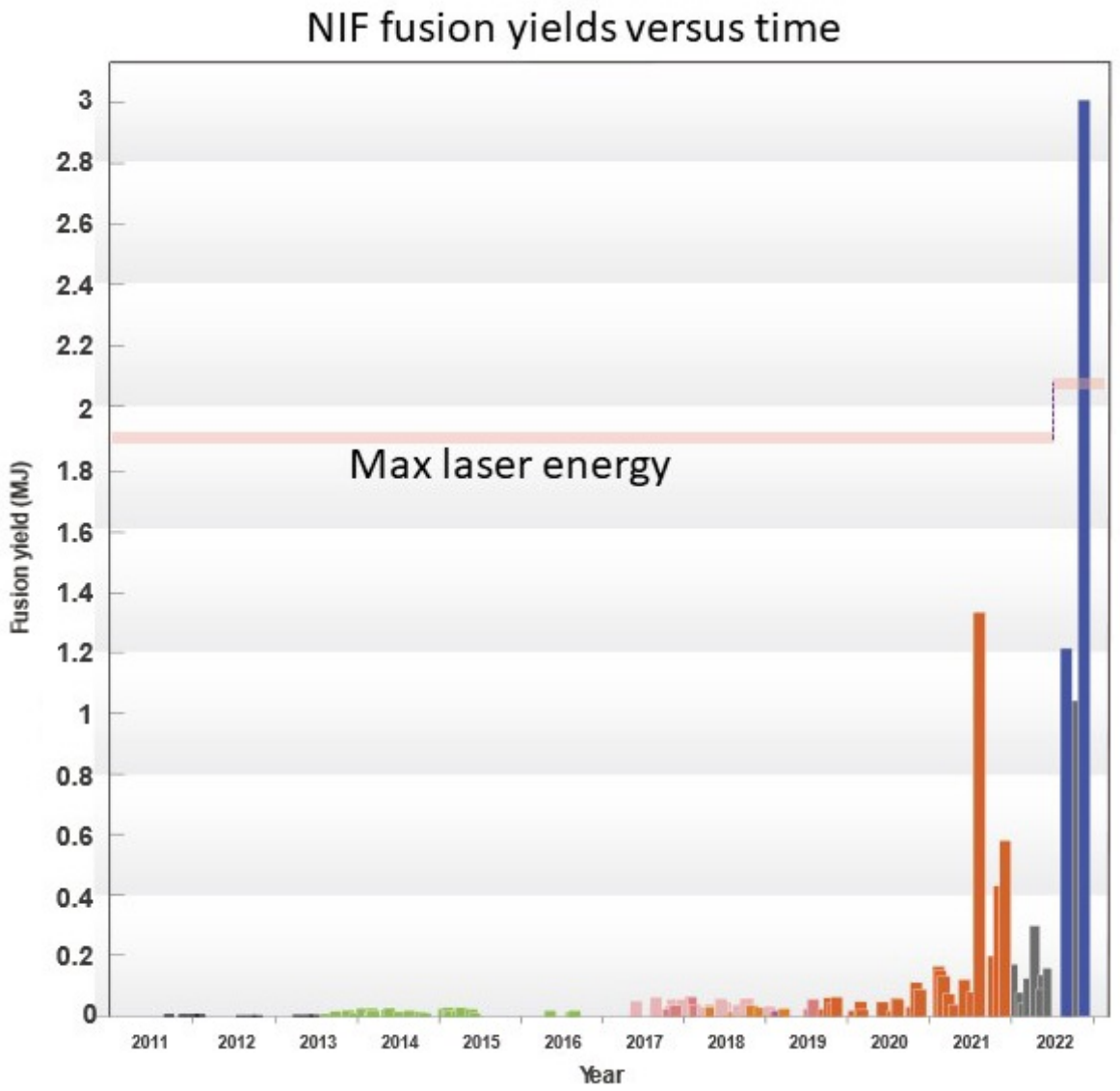
National Ignition Facility achieves ignition and $Q_{\mathrm{sci}} > 1$ in 2022

December 5th 2023: NIF produces 3MJ
of fusion energy from 2MJ of laser energy

Q_{sci} = fusion energy / energy entering vacuum vessel





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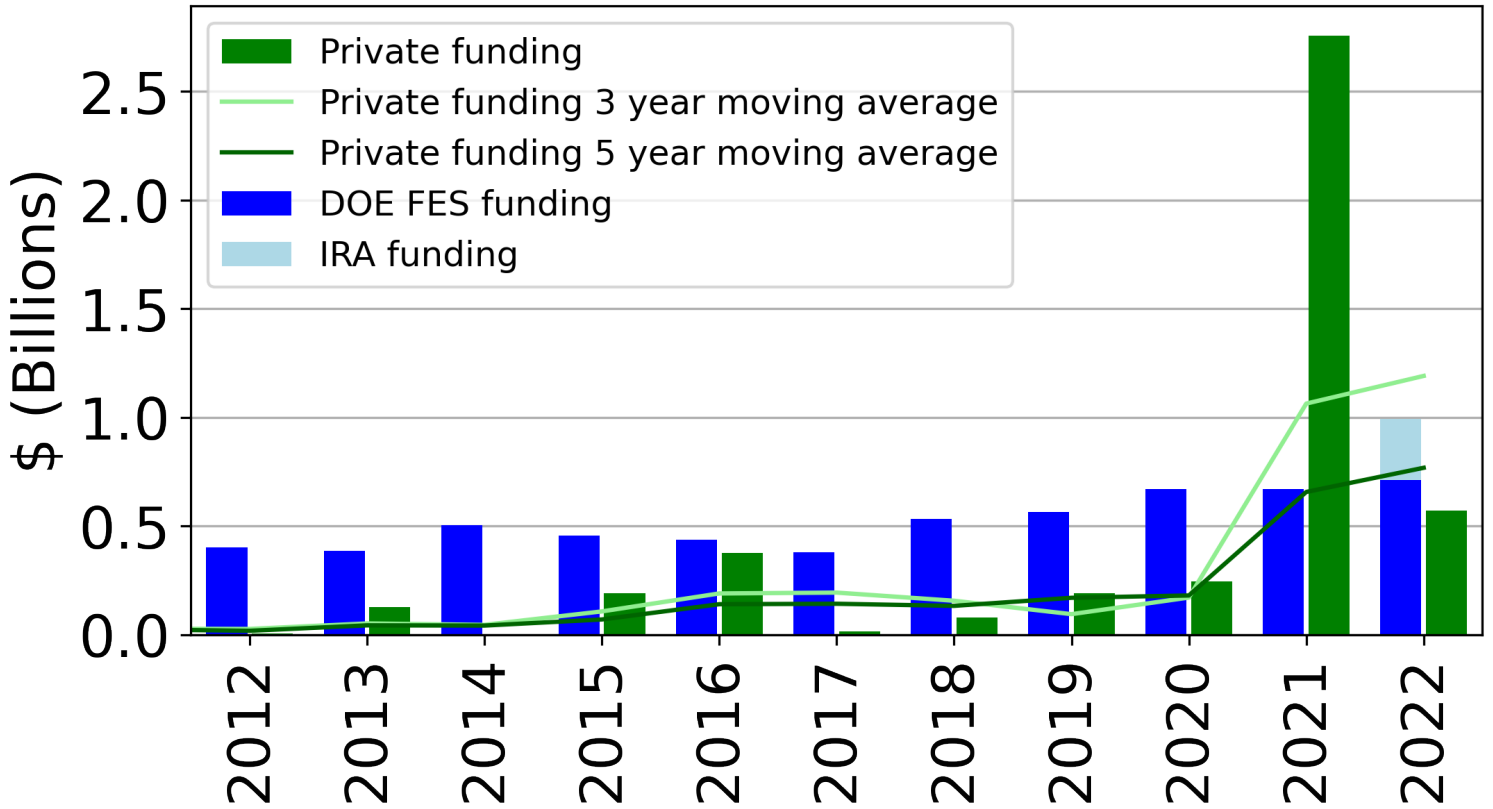
2000 to present: rise of the private fusion industry

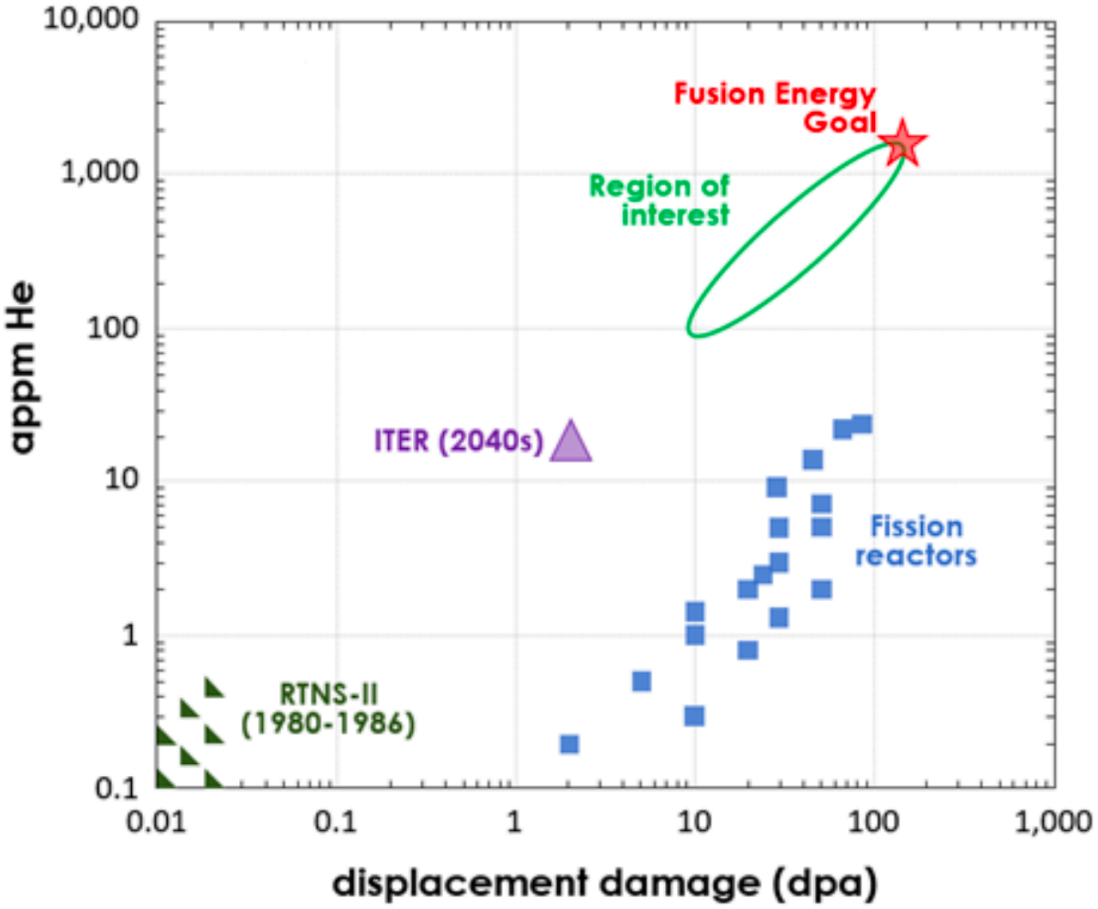
Fusion Industry Association



FIRST WALL, AND STRUCTURAL MATERIALS

Plasma facing and structural materials: neutrons

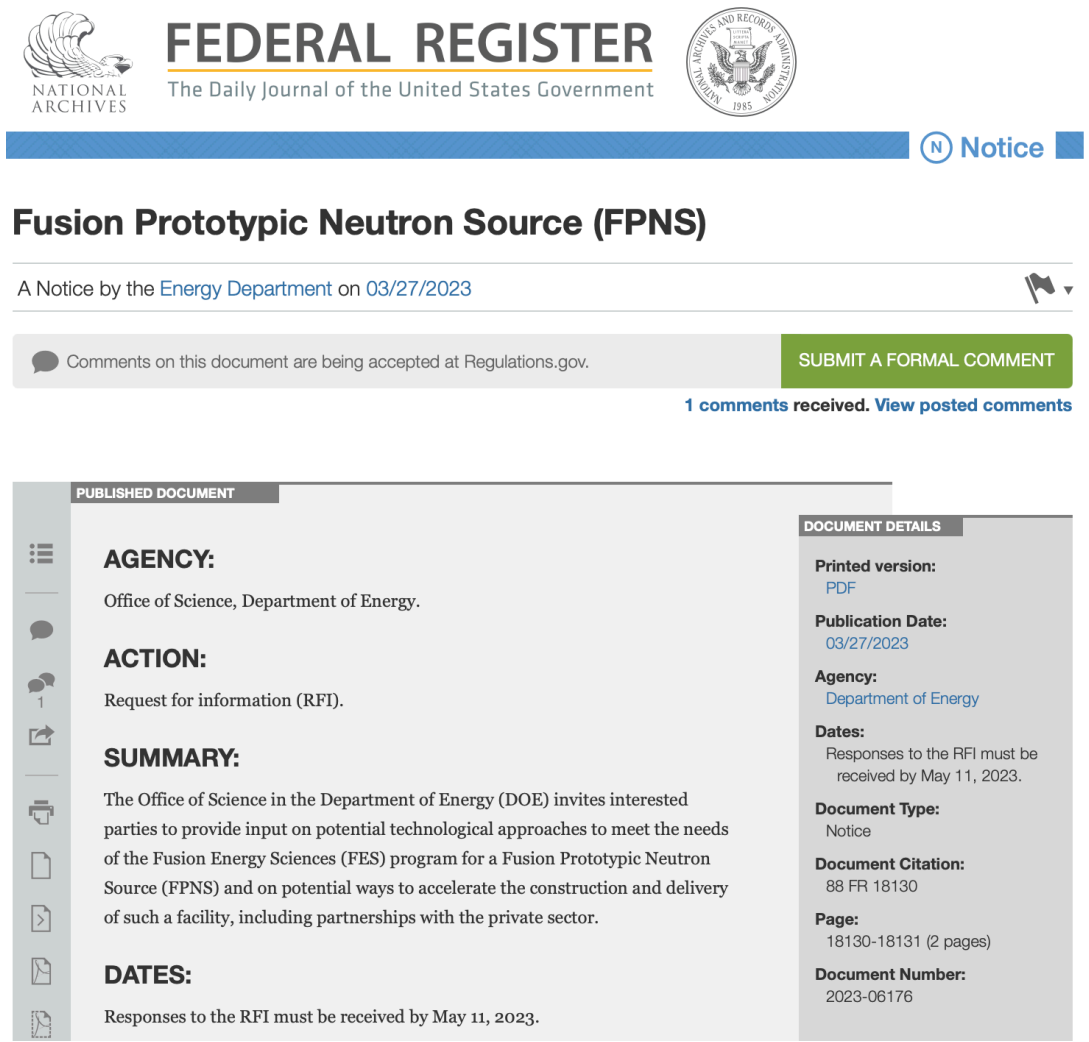
"The development of fusion energy requires structural and plasma-facing materials with sufficient dimensional stability and resistance to neutron degradation of thermal-mechanical and physical properties to support sustained operation…"



Also…
High heat flux
Corrosion
Plasma-material interactions

Program on Technology Innovation: 2022 Fusion Prototypic Neutron Source (FPNS) Performance Requirements Workshop Summary, EPRI

Fusion prototypic neutron source (FPNS) RFI



NATIONAL ARCHIVES

FEDERAL REGISTER

The Daily Journal of the United States Government

Notice

Fusion Prototypic Neutron Source (FPNS)

A Notice by the Energy Department on 03/27/2023

Comments on this document are being accepted at Regulations.gov.

SUBMIT A FORMAL COMMENT

1 comments received. View posted comments

PUBLISHED DOCUMENT

AGENCY:

Office of Science, Department of Energy.

ACTION:

Request for information (RFI).

SUMMARY:

The Office of Science in the Department of Energy (DOE) invites interested parties to provide input on potential technological approaches to meet the needs of the Fusion Energy Sciences (FES) program for a Fusion Prototypic Neutron Source (FPNS) and on potential ways to accelerate the construction and delivery of such a facility, including partnerships with the private sector.

DATES:

Responses to the RFI must be received by May 11, 2023.

DOCUMENT DETAILS

Printed version:
PDF

Publication Date:
03/27/2023

Agency:
Department of Energy

Dates:
Responses to the RFI must be received by May 11, 2023.

Document Type:
Notice

Document Citation:
88 FR 18130

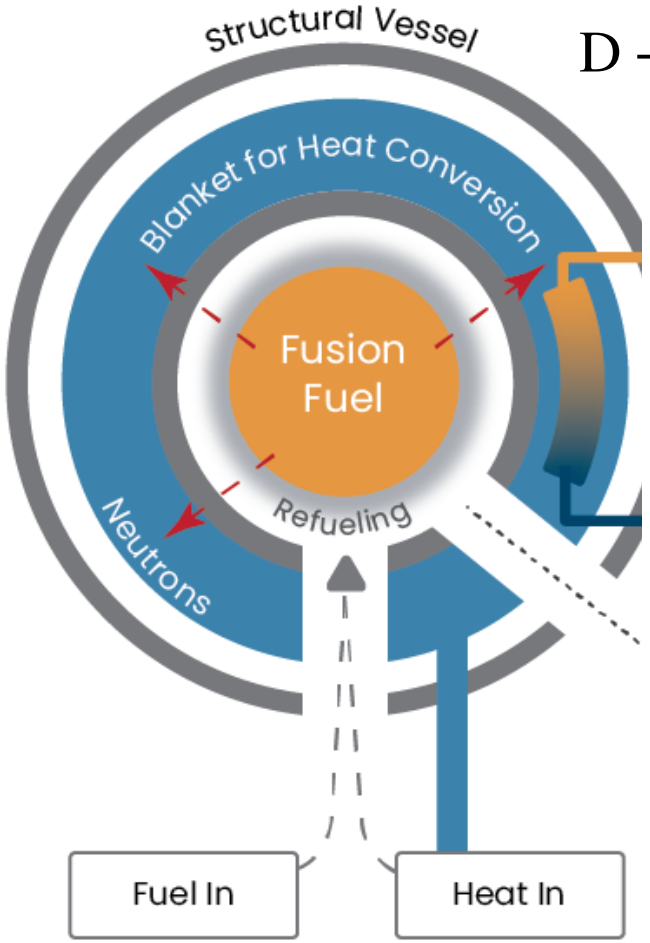
Page:
18130-18131 (2 pages)

Document Number:
2023-06176

Responses due by May 11th, 2023

D-T FUEL CYCLE CHALLENGES

Closing the deuterium-tritium (D-T) fuel cycle



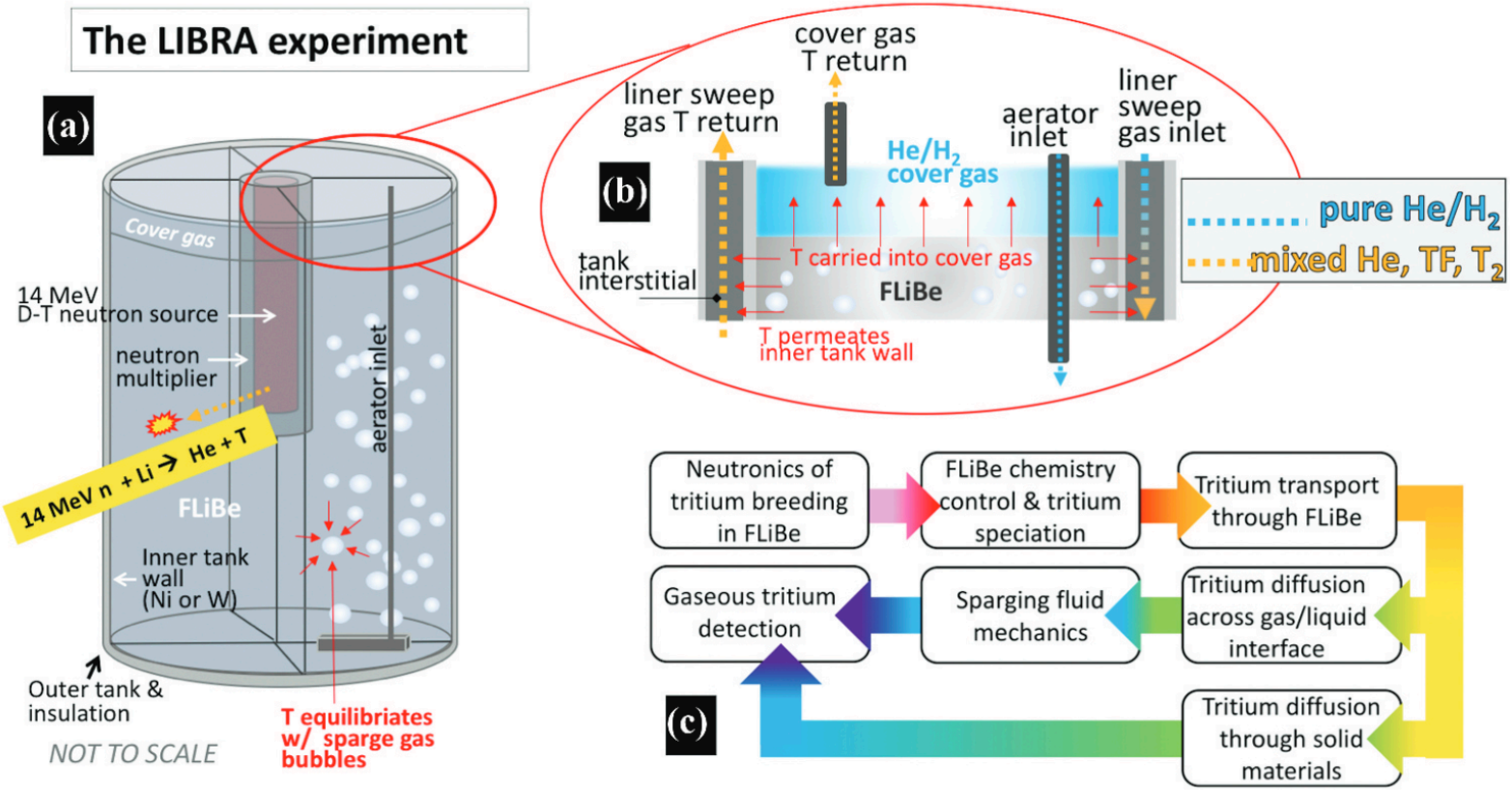
$$D + T \rightarrow \alpha\ (3.5\ MeV) + n\ (14.1\ MeV)$$

$$n + {}^{6}Li \rightarrow \alpha\ (2.1\ MeV) + T\ (2.7\ MeV)$$

- The fuel consumed in steady state for deuterium-tritium fusion is **deuterium** and **lithium-6**.
- Each neutron must generate > 1 tritium

Example ARPA-E funded project: LIBRA

Liquid Immersion Blanket: Robust Accountancy (LIBRA)



Challenges to be addressed:
Tritium accountancy
Tritium extraction
FLiBe molten salt handling

Sara E. Ferry et al. (2023) The LIBRA Experiment: Investigating Robust Tritium Accountancy in Molten FLiBe Exposed to a D-T Fusion Neutron Spectrum, Fusion Science and Technology, 79:1, 13-35

ADVANCED FUELS AND THEIR TRADEOFFS

Advanced fuels offer fewer neutrons at lower energies

Catalyzed D-D

$$\mathrm{D} + \mathrm{D} \underset{50\%}{\rightarrow} \mathrm{T}\,(1.01\,\mathrm{MeV}) + \mathrm{p}\,(3.02\,\mathrm{MeV}),$$

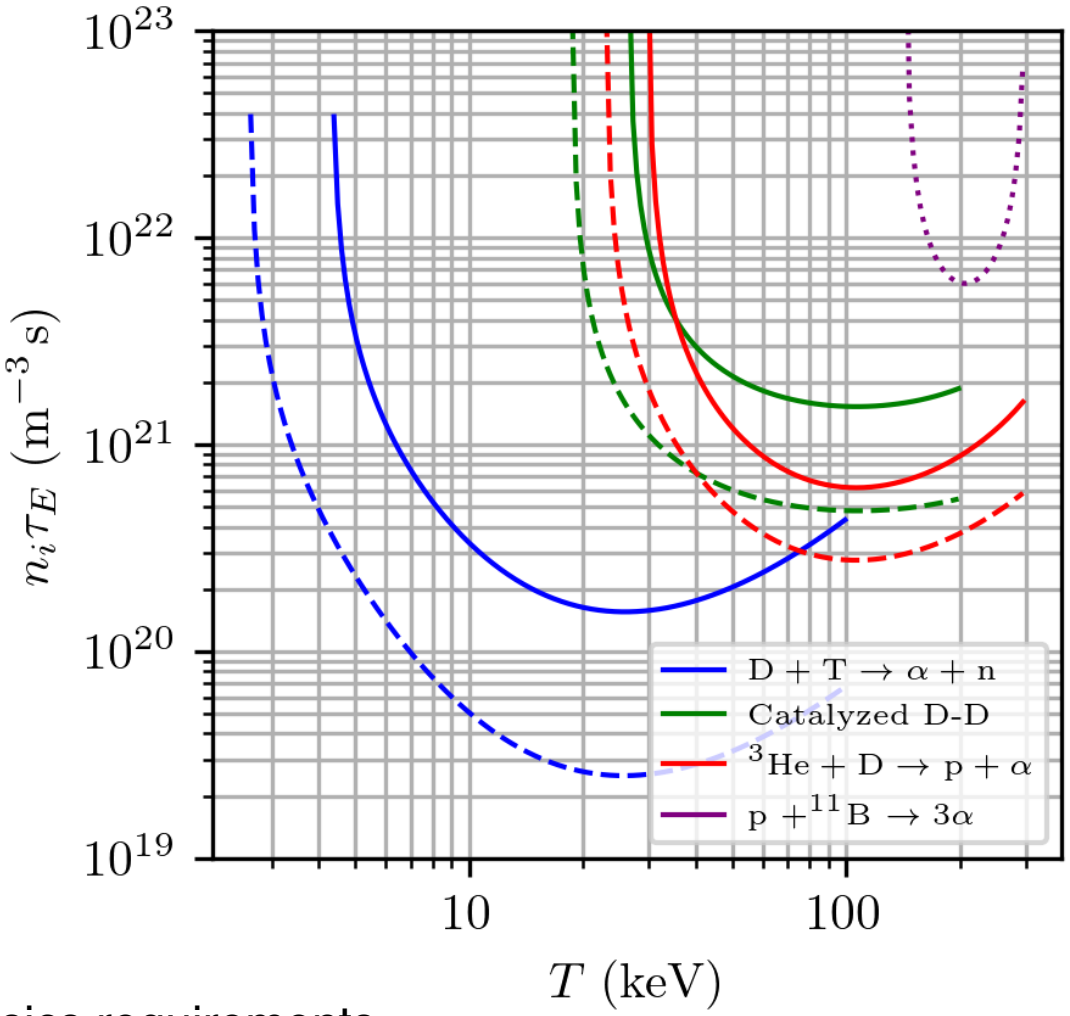
$$\mathrm{D} + \mathrm{D} \underset{50\%}{\rightarrow} {}^{3}\mathrm{He}\,(0.82\,\mathrm{MeV}) + \mathrm{n}\,(2.45\,\mathrm{MeV})$$

Deuterium - Helium-3

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow \alpha\,(3.6\,\mathrm{MeV}) + \mathrm{p}\,(14.7\,\mathrm{MeV})$$

Proton - Boron-11

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\alpha\,(8.7\,\mathrm{MeV})$$



… at the cost of more extreme physics requirements

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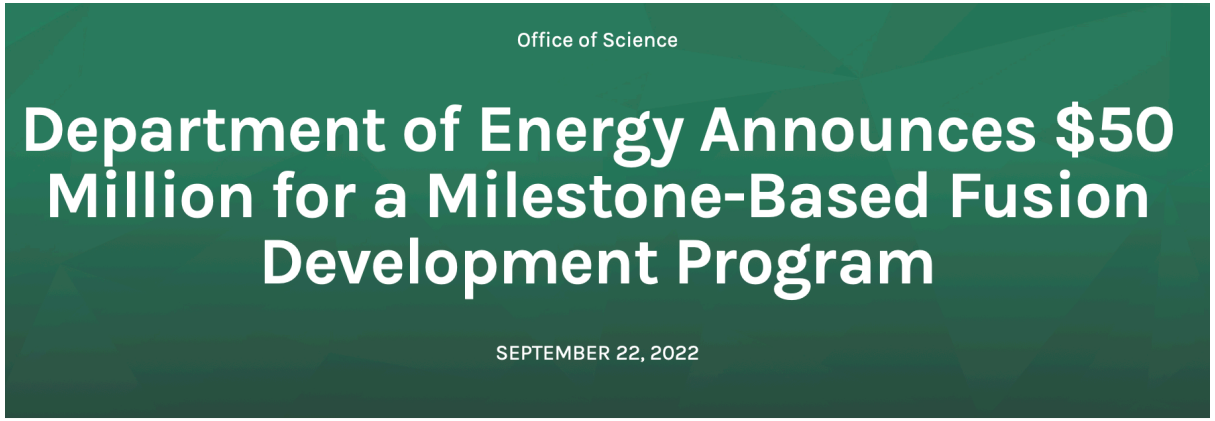
Bold decadal vision and milestone based development program



Office of Science » Department of Energy Announces $50 Million for a Milestone-Based Fusion Development Program

This new public-private partnership program is the first step toward realizing the Administration's bold decadal vision for commercial fusion energy

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Join ARPA-E!

Program Director
Location: Washington, District of Columbia, United States Full-time Partially remote

Technology-to-Market Advisor
Location: Washington, District of Columbia, United States Full-time Partially remote

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THANKS!

sam.wurzel@hq.doe.gov